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A tool for determining sheltering efficiency of mechanically ventilated buildings against outdoor hazardous agents

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A B S T R A C T

Sudden large scale outdoor releases of toxic materials may require protective actions in the affected areas, and one option is to shelter indoors. Mechanically ventilated buildings provide protection against outdoor hazardous particulate materials with varying efficiency depending mainly on the properties of the HVAC system of the building, air leakage, and the nature of the outdoor release. A tool for modelling the indoor concentrations due to outdoor contaminants has been developed and presented. The tool solves numerically the simplified mass balance equation describing the size-resolved behaviour of airborne particles and uses as input experimentally obtained data on particle concentrations outdoors, in the supply air, and indoors. By eliminating the effect of indoor sources the size-resolved indoor/outdoor (I/O) ratio for fine particles can be determined accurately, thus giving detailed information on the buildings protective capability and thereby quantitative knowledge to support emergency managers decision making.

1. Introduction

In order to protect communities from intentional or accidental releases of toxic materials questions we should at least consider are: what steps should we take to prepare for these kinds of incidents and, if necessary, how to respond to them? Furthermore, should we, for example, come back to the idea of common public shelters dedicated to the civilian population which was one of political priorities of most governments back to the times of the Cold War? The issue is still being discussed in many countries. However, the point is that due to the common uncertainty and dynamism of changes we experience in todays' world, the threats could come rapidly enough to not give us a chance to realise them; to localise a shelter and finally get to a public shelter. In many cases these shelters are far away from the place we live in or do not exist at all in close proximity. This hypothesis is confirmed by official reports which in some countries state that there is a very limited number of available places in public shelters to be used in case of a disaster or a war. For example in one of the central European countries there is only 2.9% available sheltering places of overall number of population [1]. This could bring us to the next question. Should we really consider these public shelters as an effective way of protecting the population? Shouldn't we rather focus on the protection strategy which assumes that everybody can protect themselves in the place where they in at the moment of the chemical or radiological incident, e.g. in a family house or public building. If so, what should we know about the appropriate behaviour and what is the real threat of contamination for us if we stay in this building when the incident happens? And finally, how much of dangerous materials can be transmitted from outside to inside the building?

In the event of large scale outdoor releases of hazardous materials the two primary measures to protect the public health from excessive exposure are thus mass evacuation of people from affected areas or sheltering indoors. In the sheltering option, people are typically advised to "go in, stay in and tune in [2]", close doors and windows, shut off ventilation and turn on radio for further instructions. In more detailed guidelines it is advised not to use elevators because they create a piston effect and can pump air into or out of the building, have people gather in pre-identified "shelter-in-place" rooms that have no or low air exchange with the outdoors, and have low air exchange with the rest of the building [3].

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Once the outdoor concentration has diminished to safe levels, the building should be evacuated or flushed with outdoor air. The protection can be improved with high-efficiency supply air filtration and proper operation of the HVAC system.

The main factors affecting buildings protection efficiency against outdoor toxic agents are the duration of the event and the infiltration of contaminants. The event duration depends on the source. Accidental leaks from tanks can be over or under control within few hours while during the Fukushima and Chernobyl nuclear power plant disasters the release continued for several days. The contaminant transport rate from outdoors to indoors depends both on the building and toxic material characteristics. In general, airtight buildings provide better protection than leaky ones for short term releases, and the building envelope generally removes coarse particulate materials but not significantly gaseous agents with high vapour pressure.

Since a key parameter in outdoor pollutant penetration is air exchange between the indoor and outdoor environments, several studies have been conducted to estimate the infiltration and natural ventilation rates. In an extensive investigation Langer et al. [4] used occupant-generated carbon dioxide as tracer gas to determine the nighttime air exchange rate of 450 French dwellings and found the average value to be 0.65 1/h with a standard deviation of 0.87 1/h. Taylor et al. [5] studied the effects of building characteristics and occupational behaviour on the I/O ratio of outdoor PM2.5 using building archetypes representative of Greater London area. For calculating the infiltration they used the EnergyPlus building simulation tool assuming penetration for PM2.5 to be 0.8 when windows were closed and 1.0 when open. The modelled I/O ratios varied from 0.37 to 0.74 and were lowest in low permeability houses in wintertime and highest in scenarios in summertime when windows were opened for cooling.

There have been also experimental studies of the effect of ventilation type on indoor air pollutant levels. Irga and Torpy [6] measured indoor concentrations of several contaminants in eleven different office environments in Sydney throughout one year and found clear correlation with the ventilation type and level of contaminants. The pollutant levels, including particles, were in general lowest for buildings with mechanical ventilation.

Shelter in place has also been advised to be taken as an action for public health protection during the Southeast haze episodes. Chen et al. [7] examined the indoor and outdoor size resolved particle concentrations in a typical mechanically ventilated office building during and after the 2013 haze in Singapore, and found a clear relationship between the characteristics of the ventilation system and I/O ratio of particles in the size range of 0.3–1 μm. In another study [8] the positive pressure control method was analysed by modelling using various environmental parameters and building characteristics. It was concluded that the influences of outdoor wind velocity and the leakiness of the building on preventing the entry of the outdoor particles with positive pressure control are relatively dominating. The researchers also found that for a building equipped with fibrous supply air filters, particles in the size range of 0.1–0.3 μm have the highest penetration. The indoor air cleaning method which allows outdoor particles to enter indoors first and the uses filtration to remove them, was found to be increasingly more effective with decreasing supply air filtration efficiency and building air tightness. Ward et al. [9] concluded that a representative room air cleaner in a typical US house would reduce the indoor concentration of outdoor originated particulate contaminants by 40–60% in the size range of 0.1–2 μm.

Several models have been developed to calculate sheltering efficiency of buildings. Siren [10] calculated infiltration air flows and contaminant transport inside a residential building assuming a gaseous contaminant. Jetter and Whitfield [11] determined the protection factor for a room inside a test house for various scenarios. Chan et al. [12] utilised the data from US house leakage measurements to evaluate sheltering efficiency under different chemical release scenarios. In his dissertation thesis Chan studied also the protection provided by commercial buildings with the mechanical ventilation system running [13]. In these studies it has been assumed that the duration of the incident is relatively short, up to few hours. Engelmann [14] determined a dose reduction factor (DRF) for airborne contaminants as the ratio of time-integrated airborne concentrations indoors and outdoors, and demonstrated that for long duration plumes containing respirable plutonium the DRF approaches the equilibrium indoor/outdoor ratio for particulates.

A significant fraction of radionuclides released by nuclear incidents such as nuclear reactor accidents are in the form of radioactive particles. Measurements demonstrated that after the Fukushima accident the air contained radioactive particles with activity median aerodynamic diameter (AMAD) ranging between 0.25 and 0.71 μm for ^{137}Cs, from 0.17 to 0.69 μm for ^{134}Cs, and from 0.30 to 0.53 μm for ^{131}I [15]. These are similar to the findings made after the Chernobyl accident [16,17]. Although during the Fukushima incident the airborne radioactive particles were of no concern for public health in Europe because of atmospheric dispersion and dilution along the route from Japan, the Chernobyl disaster demonstrated that the activity of particles can be orders of magnitudes higher [15–17].

In order to be able to make informed decisions the emergency response planners should be able to predict the protection capability of buildings against outdoor hazardous particles more accurately. This has been noted by Sohn et al. [18] who presented a screening level methodology by which generalised information about airborne concentrations and building occupant exposures can be predicted as a result of a pollutant release to assist decision makers in developing generic plans and responses. They also demonstrated how the lack of building specific information can result in wide uncertainties in exposure prediction.

The key factors affecting the estimation of predicted dose are the concentration and duration of the plume at a particular location, and the penetration of outdoor contaminants to indoors. Prediction of release durations is difficult because of the wide range of potential incidents. Therefore, planners should consider the possibility that the duration of a release may range from less than 1 h to several days.

Although several models have been developed for calculating the indoor contamination level due to outdoor pollutants there are still large uncertainties in the analysis results because of the uncertainties associated with the key parameters. Accurate determination of indoor to outdoor concentration ratios is challenging due to temporal variations of outdoor pollutant levels, and also due to indoor sources. The aim of this study was to develop an indoor contamination model for a mechanically ventilated building, present an experimental measurement system for determining the some of the key parameters which, when combined with information about the building and HVAC system characteristics, give the sheltering efficiency and to validate the model's performance in real-world conditions. The validation was made using ambient fine particles as simulants for outdoor contamination.

2. Model

Sheltering efficiency depends on several factors like the characteristics of the threat agents, mechanical ventilation flow rate and air filtration, and infiltration of outdoor air into buildings. A schematic of the simplified building model used in this study is shown in Fig. 1. Outdoor contaminants enter the building through the

HVAC system, and infiltration. The contaminants are removed by exhaust ventilation, deposition and exfiltration. There may also be recirculating room air cleaners which capture the contaminants as the room air flows through the filtration system of the cleaner.

Assuming complete mixing and uniform concentration inside the building, the mass balance for the contaminant concentration of specific size particles can be written as:

$$VdC = [q_{INF}PC_{OA}(t) + q_S C_{OA}(t)(1-E) - q_E C(t) - q_{AC}E_{AC}C(t) - q_{EXF}C(t) - \beta VC(t) + G]\cdot dt \quad (1)$$

where

V is the volume of the building (m^3)
C_{OA} *(t)* is the particle size-resolved, time-dependent outdoor particle concentration (1/dm^3)
C (t) is the indoor particle size-resolved, time-dependent concentration (1/dm^3)
q_{INF} and q_{EXF} are infiltration and exfiltration flow rates, $q_{INF} = q_{EXF}$ for a balanced ventilation system
P is the contaminant penetration through the building envelope
q_S and q_E are the mechanical ventilation supply and exhaust flow rates (m^3/s)
E is the removal efficiency of the supply air filter
q_{AC} is the flow rate of the air cleaner
E_{AC} is the removal efficiency of the air cleaner for the specific contaminant
G is the indoor contaminant generation rate

The term *ß* in equation (1) can be evaluated from the deposition velocity on different orientations of surfaces and their respective surface areas [19]:

$$\beta = \frac{v_{du}A_F + v_{dv}A_W + v_{dd}A_C}{V} \quad (2)$$

The variables in equation (2) are explained in Table 1. A_F is the area of upward facing surfaces; A_W is the area of vertical surfaces; A_C is the area of downward-facing surfaces and V is the room volume.

Following Mosley et al. [20], the main mechanisms of penetration of particles was assumed to be due to diffusion and deposition in a crack

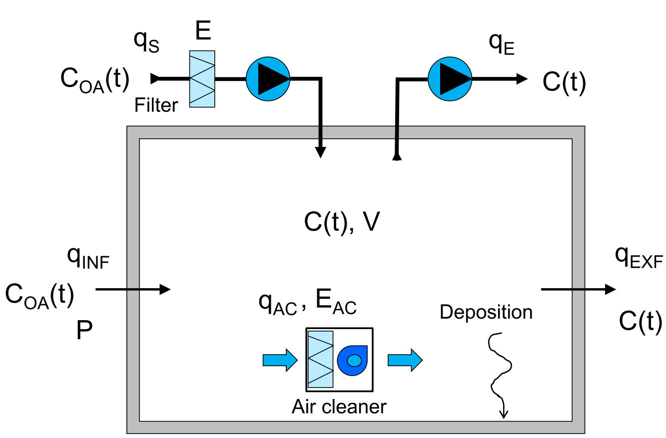


Fig. 1. Schematic of the model showing key processes in infiltration and removal of airborne contaminates.

$$P = P_d P_g \quad (3)$$

where P_g is the penetration factor associated with gravitational settling alone, and P_d is the penetration associated with particle diffusion:

$$P_d = \exp\left(-\frac{1.967\,DL}{h^2\,u}\right) \quad (4)$$

D is the particle diffusion coefficient, L is the depth of the crack, $2h$ is the height of the crack, u is the mean flow velocity in the crack. The gravitational settling was calculated as

$$P_g = 1 - \frac{v_s\,L}{2h\,u} \quad (5)$$

where v_s is the settling velocity.

If the mechanical ventilation supply and exhaust flows are balanced ($q_{VS} = q_{VE}$), the impact on infiltration is insignificant because the balanced system does not change pressure across the building leaks. As a result, the total ventilation flow rate is the addition of the balanced fan flow and the natural infiltration [21], and infiltration and exfiltration flow rates are equal.

To solve equation (1) the parameters in the model need to be determined. Some of them may be readily available like the volume of the building and mechanical ventilation flow rates, but there are also parameters which need to be measured or estimated. The following chapters describe in detail how this can be done. A key parameter is the outdoor concentration, which usually varies with time of day. Therefore an analytical solution to equation (1) is not possible in general and hence a numerical solution is the only option. After determining the necessary parameters, the equation can be solved numerically using a basic forward marching scheme with time step:

$$C(t_{i+1}) = C(t_i) + \Delta C_i \quad (6)$$

$$\Delta C = [q_{INF}PC(t_i)_{OA} + q_S C_{OA}(t_i)(1-E) - q_E C(t_i) - q_{AC}E_{AC}C(t) - q_{EXF}C(t) - \beta C(t) + G]\cdot\frac{\Delta t}{V} \quad (7)$$

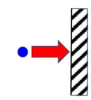
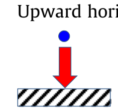
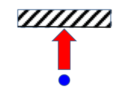
In these exercises, the time step used was 3 min, corresponding to the data storage interval of the measurement system.

3. Field experiments

3.1. Measurement system

To determine the key parameters and validate the model, a measurement system as shown in Fig. 2 was designed and constructed for field tests. The test site was a commercial building in an urban area about three kilometres from the Helsinki city centre and 200 m from a main entryway to the city. The four-storey building included a gym, offices, storage facilities and a parking garage, and it was mechanically ventilated with two separate air handling units. The building footprint is L-shaped with maximum external dimensions of 58 and 38 m. It was constructed in the 1980s of precast concrete elements. The measurement system was installed in the air handling unit serving the offices and the gym with a total volume of about 4000 m^3. The supply and exhaust flow rates were 1.0 m^3/s corresponding to an air exchange rate of 0.9 1/h, and the fans were set to run at constant speed during the measurement session. The air handling unit was equipped with a F7 grade supply

Table 1
Equations used in the particle deposition modelling.

Equation	Explanation
$I = 3.64\, Sc^{0.67}(a-b)+39$ $a = \frac{1}{2}\ln\left[\frac{(10.92\, Sc^{-1/3}+4.3)^3}{Sc^{-1}+0.0609}\right] + \sqrt{3}\tan^{-1}\left[\frac{8.6-10.92\, Sc^{-1/3}}{\sqrt{3}\, 10.92\, Sc^{-1/3}}\right]$ $b = \frac{1}{2}\ln\left[\frac{\left(10.92\, Sc^{-\frac{1}{3}}+r\right)^3}{Sc^{-1}+7.67\cdot 10^{-4}\, r^3}\right] + \sqrt{3}\tan^{-1}\left[\frac{2\, r^3-10.92\, Sc^{-1/3}}{\sqrt{3}\, 10.92\, Sc^{-\frac{1}{3}}}\right]$	$Sc = \nu/D$
$v_{dv} = \frac{u^*}{I}$	Vertical surface 
$v_{du} = \frac{v_s}{1-\exp\left(-\frac{v_s I}{u^*}\right)}$	Upward horizontal surface 
$v_{dd} = \frac{v_s}{\exp\left(\frac{v_s I}{u^*}\right)-1}$	Downward horizontal surface 
$v_s = \frac{C_c\, \rho_p\, d_p^2\, g}{18\, \eta}$	Settling velocity
η is the dynamic viscosity of air ν is the kinematic viscosity of air ρ_p is the particle density C_c is the Cunningham slip correction factor D is the Brownian diffusivity of the particle d_p is the particle aerodynamic diameter g is the gravitational acceleration u* is the friction velocity	Abbreviations

air filter and a fixed-plate heat exchanger.

The system consisted of air sampling, a valve mechanism, a particle counter (Met One) and computer that controlled the system and recorded the measured data. In addition to particle concentration and size distribution, temperature (T), relative humidity (RH) and the pressure difference of the supply air filter were also measured. The data was sent wirelessly to a server, where the data was analysed, facilitating a remote real-time measurement of the air quality and filter performance.

The sample lines made of copper tubes were designed so that they were similar in size and length to minimise errors due to losses. The sampling line had also a zero filter so that the zero level of the particle counter could be checked during each sample cycle.

The particle data was collected from three locations: 1) make-up air (outdoor ambient air), 2) supply air (downstream of the filter), and 3) exhaust air (average indoor air) as shown in Fig. 2. Vaisala transmitters were used for measuring the temperature and relative humidity of the supply air. The system stored the collected data at three minute intervals. The data included particle number in different sizes (0.3–0.5 μm, 0.5–0.7 μm, 0.7–1 μm, 1–2 μm, 2–5 μm, and >5 μm) upstream and downstream of the supply filter, and in the exhaust air. In addition, the data contained the measured temperature and air humidity, and pressure drop over the filter.

The system was run for four months. The removal efficiency of supply air filters was measured continuously and sent for analysis. The results were then used to validate the developed model.

4. Results

4.1. Temperature and humidity

An example of the measured temperature and humidity are presented in Fig. 3. The supply air temperature (before treatment) typically peaked in the afternoon and showed a minimum in the early morning while the diurnal variation of relative humidity was the opposite of the air temperature. However, the moisture content expressed as the ratio of water vapour mass to the dry mass of air remained more constant.

4.2. Particle entry due to mechanical ventilation

Mechanical ventilation brings filtered outdoor air into the ventilated space. The particle entry rate into the indoor environment due to supply air is the product of the air flow rate and penetration of the supply air filter (Filter penetration = 1-E). In the studied case, the supply air flow rate was 1.0 m^3/s and the measured removal efficiency of the supply air filter is shown in Fig. 4. As can be seen, the fractional efficiency depends strongly on the particle size so that it is minimum for the smallest particles and increases with particle size.

4.3. Particle entry due to infiltration

The particle entry rate due to infiltration is the product of infiltration flow rate and penetration fraction of particles. Infiltration, or uncontrolled air leakage, is one of the key parameters affecting the accuracy of simulations. In general, it can be estimated using the tracer gas method or a pressurisation test [22]. Here a different approach was adopted. The infiltration flow rate can be solved using equation (1) assuming that there are no indoor sources and that the deposition mechanism is insignificant, and the penetration of particles is close to unity. These last two conditions can be approximated with the smallest size range (0.3–0.5 μm) of the measured particles [23]. With these assumptions, the infiltration to

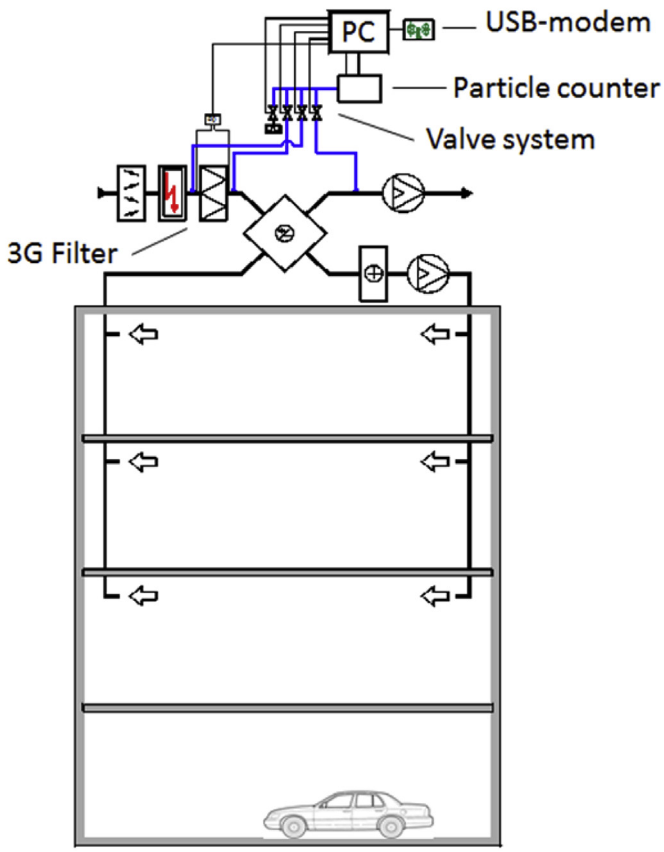


Fig. 2. Principle of the test arrangement and ventilation system in the test site.

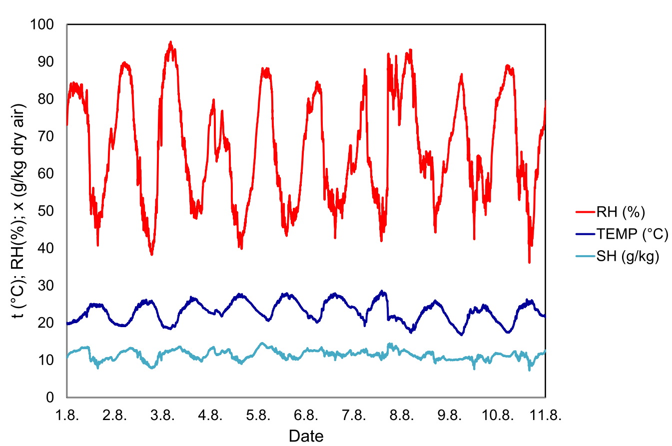


Fig. 3. Measured supply air temperature and relative humidity (RH). The calculated specific humidity (SH) is expressed as g of water vapour in kg of dry air.

mechanical ventilation flow ratio can be calculated as

$$\frac{q_{INF}}{q} = \frac{\frac{V\Delta C}{q\Delta t} - ((1-E)\,C_{OA} - C)}{PC_{OA} - C} \tag{8}$$

where the removal efficiency E of the filter for a specific particle size can be achieved from the measured values. In the derivation of Equation (8) it has been assumed that the ventilation system is balanced so that the mechanical supply and exhaust flow rates are equal at their design values (1.0 m^3/s), meaning that infiltration and exfiltration rates are also equal as demonstrated by Hurel et al. [21].

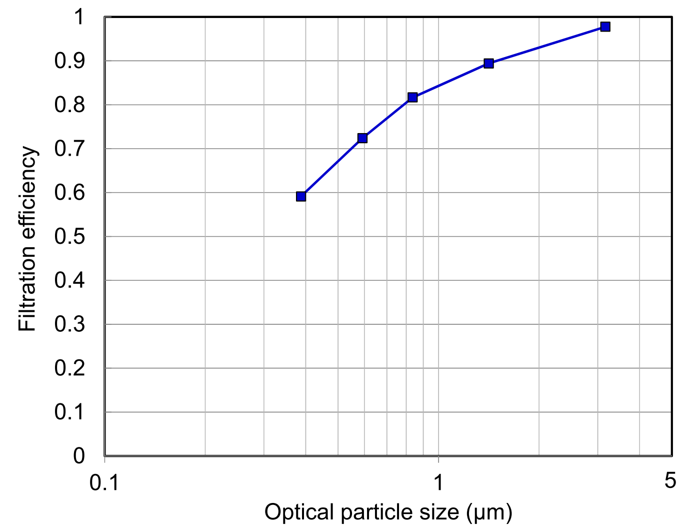


Fig. 4. Measured fractional efficiency of the supply air filter.

This assumption, however, was not experimentally confirmed because accurate measurement of airflow rates in the AHU machine room where the measurement system located was not feasible.

The leakage air flow ratio was determined utilising the calculated indoor concentrations so that the indoor sources were omitted. The leakage flow varied somewhat over time, as seen from Fig. 5. During the 24 h observation period the ratio was 0.59 ± 0.04, corresponding to an air exchange rate of 0.53 ± 0.03 1/h. This is somewhat higher than in previous studies. Chan [13] calculated the infiltration rates of US commercial buildings and found them to be lognormally distributed with GM = 0.35 1/h and GSD = 2.1 1/h. The higher than average value may be due to the elevator shaft and stairwell, which typically add to the overall air leakage of the building. However, the ratio of infiltration to mechanical ventilation (0.59) is well within the values 0.1 to 1.0 observed for commercial buildings [13].

4.4. Particle losses due to deposition

Particle losses were calculated for the measured size range. The friction velocity u* used in the deposition calculations was

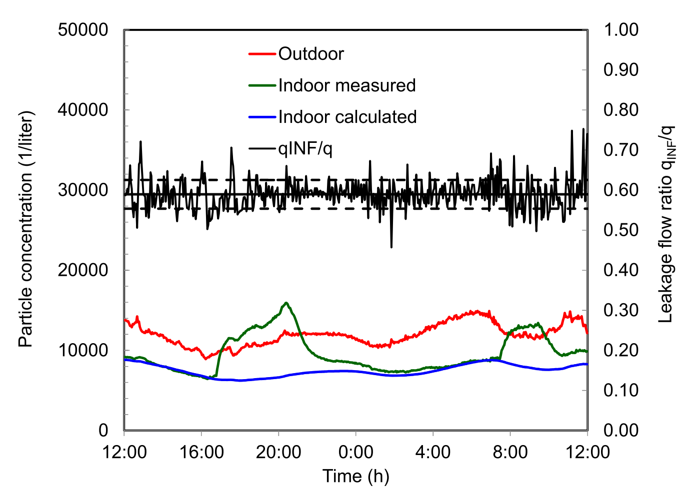


Fig. 5. Estimation of infiltration rate with the aid of measured concentrations of 0.3–0.5 µm particles.

estimated to be 1 cm/s based on an average room air velocity of 0.2 m/s. The results are presented in terms of air exchange rate in Fig. 6. For comparison, the product of leakage flow rate (0.59 m^3/s) and penetration through the building envelope is also shown.

4.5. Calculation of I/O ratio

In the model validation, the measured outdoor concentration was used as an input for calculating indoor concentration. The indoor concentration was then solved by integrating Equation (1) numerically for each time step for which readings were taken (every 3 min). Examples of the measured and predicted concentrations with the model for different size ranges are presented in Figs. 7–9.

The focus of this work was to examine the penetration of outdoor contaminants indoors, and no attempts were made to model the indoor source G which was set to zero. Consequently, the modelled indoor concentrations deviated significantly from the measured ones during morning and evening activities.

As expected, strong variations in both outdoor and indoor particle concentrations occurred according to the ambient conditions. It is seen that the effects of these outdoor concentration variations affected the indoor concentrations, and that these effects could be fairly well predicted with the model. The peaks in the indoor concentrations sometimes exceeded the outdoor levels, and it is likely that they are due to indoor particle sources. Such indoor sources do not affect the sheltering efficiency of buildings and therefore should be separated when calculating the protection capability.

To eliminate the effect of indoor sources, the indoor concentrations can be based on the calculated values which assume that there is no particle generating activities indoors. Because the modelled concentrations closely followed the measured values during night-time when the building was empty, it is likely that they predict the daytime concentrations accurately as well. Therefore, for calculating the indoor to outdoor ratio for different particle size ranges, the modelled indoor values can be used for reference.

The I/O ratios for the same measurement period as in Figs. 7–9 are presented in Fig. 10. As for comparison, the I/O ratio is presented also for the untreated raw data. It is seen that the I/O ratios based on the calculated indoor concentrations are consistently lower and have smaller deviation than those based on the raw data, which includes also the particles generated by indoor sources.

Fig. 10 shows also the measured activity median aerodynamic

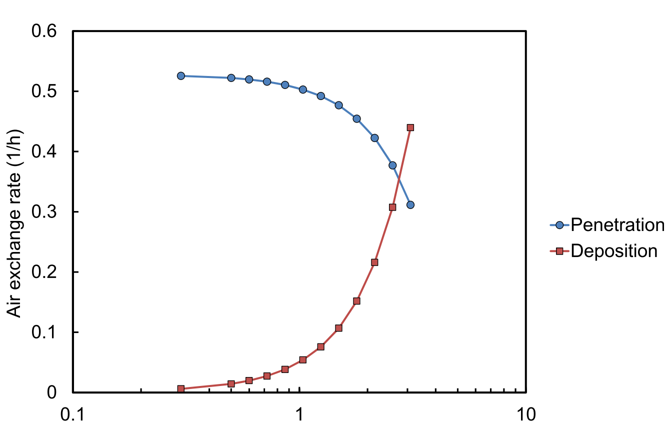


Fig. 6. Calculated particle deposition and particle penetration rate as a function of particle size.

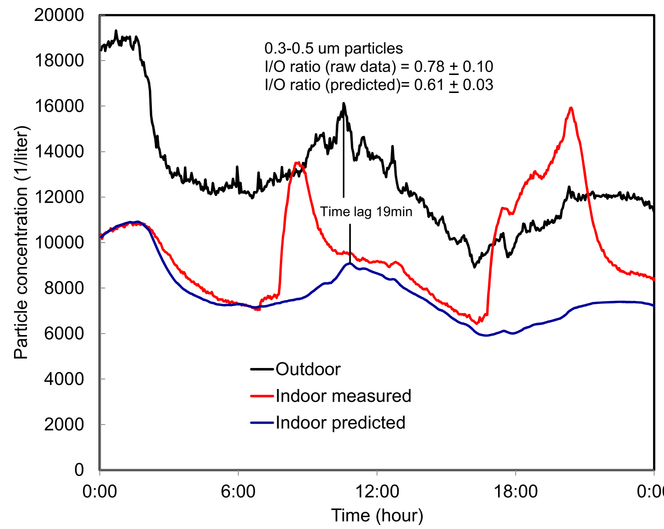


Fig. 7. Measured and calculated outdoor and indoor particle concentrations in the size range of 0.3–0.5 µm.

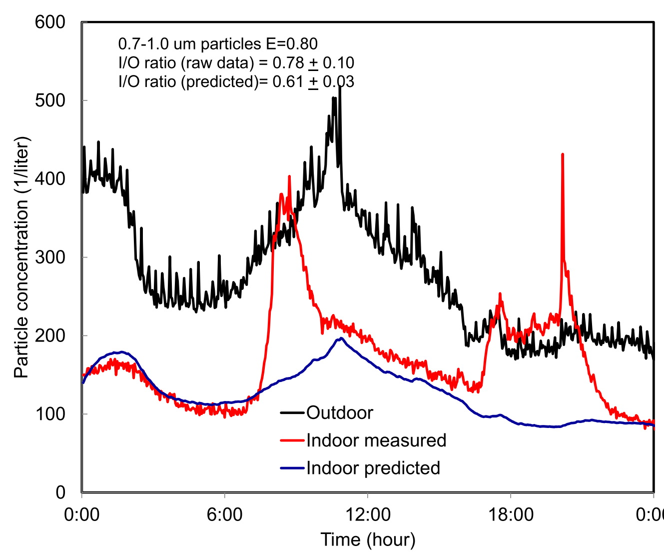


Fig. 8. Measured and calculated outdoor and indoor particle concentrations in the size range of 0.7–1.0 µm.

diameter ranges for specific radionuclides during the recent nuclear disasters [15,17]. The optical particle counter used in the experiments could not measure down to the smallest size ranges observed in the radioactive particles, but for the two smallest measured size ranges the average I/O ratio varied from 0.48 to 0.65.

4.6. Sheltering efficiency

Based on the characteristics of the field test building, indoor concentrations were calculated for outdoor exposure times of 0.5, 1, 2, 4 and 8 h with a ventilation air exchange rate of 0.9 1/h and an air leakage exchange rate of 0.53 1/h. For simplicity, the outdoor concentration was assumed to be zero before the plume arrived, 100 as it was passing the building and then dropped instantly back to zero. The resulting indoor concentrations are presented in Fig. 11. The indoor concentrations were calculated for three different cases: 1) ventilation is shut off and the air exchange through the building envelope is by infiltration only ($q = 0\ m^3/s$, $q_{INF} = 0.53$ 1/h), 2)

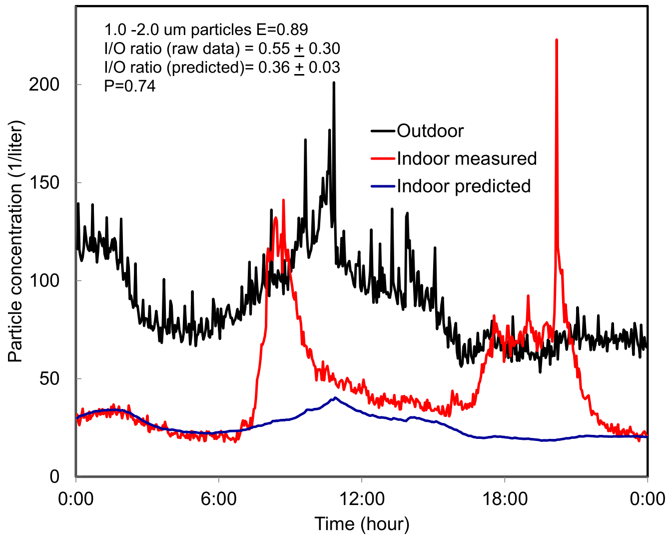


Fig. 9. Measured and calculated outdoor and indoor particle concentrations in the size range of 1.0–2.0 μm.

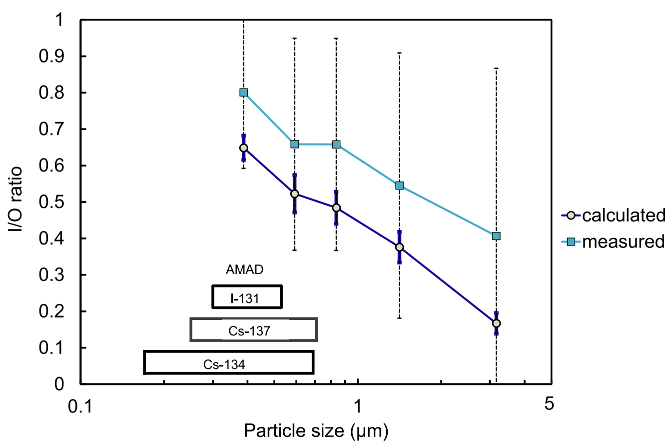


Fig. 10. Measured and calculated indoor to outdoor (I/O) ratios for different particle sizes. Standard deviations of the measurements are shown by vertical bars.

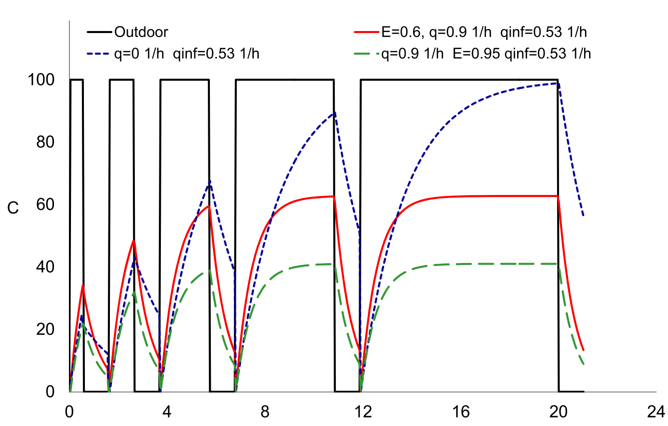


Fig. 11. Simulated indoor concentrations in different cases.

current configuration (mechanical ventilation flow rate = 0.9 1/h, infiltration = 0.53 1/h and E = 0.6 for 0.4 μm sized particles), and 3) current configuration but the efficiency of the supply air filter is 0.95. Exposure is illustrated as the area under the concentration curves. Dose reduction factors (DRF) for contaminants whose effects vary linearly with the airborne concentration can be determined by dividing the area under the indoor concentration curve by the area under the outdoor concentration curve [14]. It is assumed that the contaminant is evenly distributed inside the building and that the sheltering is terminated immediately after the toxic cloud passage. The assumption of uniform concentration inside the building is a simplification but it allows the comparison of exposure during different release times. In the experiments the indoor concentration was measured in the exhaust air giving an average value of the ventilated space. Based on empirical observations, the neutral pressure location of buildings is largely unaffected by operating the mechanical ventilation system [13] implying that the balanced ventilation system does not affect infiltration rates. It is seen that when the ventilation is shut off, the cumulative indoor exposures approach the cumulative outdoor exposures as the occupancy time increases. On the other hand, the mechanical ventilation and filtration of supply air reduces the exposure, and the reduction is larger when the filtration efficiency is better. However, even if the supply filter removed all the contaminants from the supply air there would still be contaminants due to infiltration.

The calculated dose reductions for the three different cases are presented in Fig. 12. It is seen that for the studied office building (with F7 grade supply air filters) the current guidelines – shutting ventilation to minimise contaminant penetration indoors – is more efficient in protecting occupants for releases that last less than about 2.5 h. For longer releases the occupant exposure could be reduced more if the ventilation were running as normal. The DRF for a building with stopped ventilation eventually approaches unity while for the building with ventilation on, the limit value is

$$C = \frac{(1-E)q_S + q_{INF}}{q_S + q_{INF}} C_{OA} \tag{9}$$

If the supply air filter in the example case had an efficiency of 95%, the occupant exposure would be lower for the running

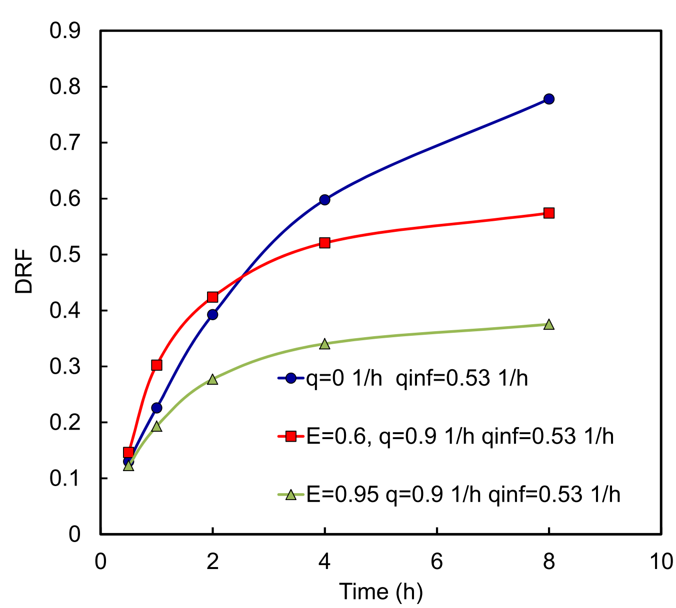


Fig. 12. Dose reduction factor in different cases and exposure times.

ventilation even for outdoor plumes lasting 30 min. The challenge, however, is to improve the filtration efficiency without increasing the pressure drop over the filter and thus possibly reducing the air flow rates.

5. Discussion

The presented model simplifies the indoor air environment in different ways. First, it represents the entire volume of the building as a single compartment with uniform concentration. More detailed information about spatial variations inside the building may be achieved with multi-compartment models, as airflows can vary substantially between floors and between different rooms on the same floor [24]. Moreover, there are uncertainties in the particle penetration and deposition calculations. However, despite the simplifications, the model worked reasonably well for the prediction of the indoor concentration.

The key parameters determining a mechanically ventilated building's sheltering efficiency against ambient air pollutants are contaminant entry rate through infiltration and supply air. This study presents a convenient method to determine both these parameters on the basis of the characteristics of the building and its HVAC system, and the measured particle concentrations. The leakage flow rates depend on meteorological conditions like wind velocity and direction, and temperature difference between indoors and outdoors [6] so the measured air infiltration rates are representative for the prevailing weather conditions during the tests. In more comprehensive studies, the average annual infiltration has been calculated using 1-h time steps and Typical Meteorological Years weather data [25].

During the experiments performed in August 2014, the average supply air temperature was 22.9 °C and it varied between 16.7 and 28.6 °C (Fig. 3). In the same month, the average wind velocity was 3.2 m/s [26]. Because of the relatively small temperature differences between outdoor and indoor temperatures, it is likely that the stack effects were small and the air leakage during the tests was mainly wind driven.

The measurement system used an optical particle counter (OPC) for counting and sizing of the particles. OPCs count pulses of scattered light from particles, and the amount of light a particle scatters can vary with the shape and reflectivity of the particle. As a consequence, the conversion from optical to aerodynamic diameter is dependent on particle composition and varies over time. Therefore the measured particle sizes are optical diameters and may not be identical to the aerodynamic diameter as assumed in the model.

In principle, indoor to outdoor ratios can be resolved by particle concentration measurements in the absence of indoor activities [24,27]. However, this may not be feasible in buildings with continuous occupancy. Moreover, in many office buildings the mechanical ventilation is turned off during the night making the determination of I/O ratio impossible. Therefore, in order to determine buildings sheltering efficiency, it is necessary to be able to separate the indoor sources from the outdoor originated contaminants.

The presented method can also be used to estimate the protection efficiency against other particulate contaminants causing a health hazard to the public. Such hazards are caused by, e.g. forest fires and agricultural burning (which produce a large number of submicron particles containing harmful constituents [28]), and by air pollution episodes.

Improving filtration efficiency increases protection. Increasing filter efficiency is one of the few measures that can be implemented in advance to reduce the consequences of outdoor release of a hazardous CBR agent. However, upgrading filtration is not as simple as merely replacing a low-efficiency filter with a higher efficiency one. Typically, higher efficiency filters have a higher pressure loss, which will result in airflow reduction through the system, and the magnitude of the reduction is dependent on the design and capacity of the HVAC system. If the airflow reduction is substantial, it may result in inadequate ventilation, and reduced protection [29]. Research work is going on to study the possibility of increasing the removal efficiency with electrically enhanced filtration without increasing the pressure drop caused by filters.

6. Conclusions

A tool consisting of a model for calculating the transport of outdoor contaminants indoors and a measurement system to determine key parameters affecting protection provided by buildings against outdoor pollutants has been developed. The performance of the tool was validated in field experiments conducted in a test site. The model is relatively simple but can predict the time dependent size specific indoor particle concentrations of outdoor origin fairly well after the key parameters have been determined. The tool may be useful for authorities responsible for emergency management to give quantitative knowledge to support their decisions when planning public protective actions.

In mechanically ventilated buildings, the main factors affecting protection against outdoor CBRN threats are ventilation flow rate, supply air filtration efficiency for the threat agent and infiltration of contaminants. To shelter against sudden contamination events, the current recommendations are to go in, stay indoors, close windows and doors and shut ventilation off. While this is an effective way to protect people from short-term releases of hazardous materials, during long-lasting releases it may be more beneficial to run the ventilation continuously to minimise occupant exposure, provided that the supply air filter is effective against the threat agent in question. The sheltering efficiency against airborne radionuclides can be improved by enhancing the filtration efficiency against submicron particles, if the modifications do not affect ventilation air flows.

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